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Grid-connected versus stand-alone energy systems for decentralized power—A review of literature

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ABSTRACT

The decentralized power is characterised by generation of power nearer to the demand centers, focusing mainly on meeting local energy needs. A decentralized power system can function either in the presence of grid, where it can feed the surplus power generated to the grid, or as an independent/stand-alone isolated system exclusively meeting the local demands of remote locations. Further, decentralized power is also classified on the basis of type of energy resources used—non-renewable and renewable. These classifications along with a plethora of technological alternatives have made the whole prioritization process of decentralized power quite complicated for decision making. There is abundant literature, which has discussed various approaches that have been used to support decision making under such complex situations. We envisage that summarizing such literature and coming out with a review paper would greatly help the policy/decision makers and researchers in arriving at effective solutions. With such a felt need 102 articles were reviewed and features of several technological alternatives available for decentralized power, the studies on modeling and analysis of economic, environmental and technological feasibilities of both grid-connected (GC) and stand-alone (SA) systems as decentralized power options are presented.

Contents

1. Introduction

Electricity is accepted as one of the driving forces of the economic development of all the nations. The challenge of

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continuously generating electricity and meeting the growing demands is daunting for both developed and developing countries, exerting tremendous pressure on the energy infrastructure. In developing countries where more than 50% of the population resides in rural regions, cost of delivered electricity becomes very expensive and unaffordable to the rural poor giving rise to reduced standard of living and social inequity. For example, in India, a very high concentration of the population (more than 70%) is living in rural regions and around 40% of the total population lives without any access to modern energy services [1]. To keep pace with the current growth rate of demand for electric power, the primary energy supply has to be increased threefold and power generation has to be increased fivefold, for which 3% of the nation's GDP has to be invested annually [2,3].

The high costs of delivered electricity can be attributed to strong dependence on centralized energy systems which operate mostly on fossil fuels and require huge investments for establishing transmission and distribution grids that can penetrate remote regions [4]. Further more, the fossil fuel combustion results in the emission of obnoxious gases rising concerns about the climate change and other health hazards.

In order to counter these problems there is a strong need for alternative systems of power generation and distribution. Unlike the centralized energy systems, on the other hand, decentralized energy systems are mostly based on renewable energy sources, operate at lower scales (a few kWh scale) both in the presence and absence of grid, and easily accessible to remote locations because of generation of power in the propinquity of demand site. Therefore, implementation of decentralized energy systems can handle the rural electrification imbroglio effectively by providing environmentally benign, sustainable and reliable energy supply. Globally, the total share of decentralized power generation in the world market increased to 7.2% in 2004, up from 7% in 2002 [5]. In the case of new capacity addition for power generation, output from decentralized generation saw a tremendous growth from 13% in 2001 to 25% in 2005 [6]. In 2006, 36% of the electricity generated from capacity addition was of decentralized type. Considering the advantages decentralized systems offer, the forecasts have predicted a further increase in the share of decentralized power systems in the global energy scenario [7]. If decentralized energy strategy is adopted, total worldwide savings are estimated to reach 2.7 trillion dollars by 2030 [5,8].

2. Extent of decentralization

The implementation of decentralized energy systems depends upon the extent of decentralization. At village decentralization, the system is managed by local participation and energy is supplied to meet the local needs. In few cases, the excess power may be supplied to the grid. On the other hand it is also possible to have industry level decentralization, in which case the power generated as a by-product of industrial process (as in bagasse co-generation) is used mainly to cater to its own needs with any surplus being fed into the grid. The extent of decentralization also determines whether the system operates in either grid-connected (GC) or stand-alone (SA) mode.

2.1. Grid-connected systems

We can distinguish two types of grid-connected systems. In the first type, the GC system's main priority is to cater to the local needs for electricity and any surplus generation will be fed into the grid, and when there is shortage electricity is drawn from the grid. The other option is utility scale, wherein decentralized stations are managed by the utilities in the same way as large electric power plants. Any output of the GC systems is fed into the central utility grid without paying heed to the local needs. Some of the important features of GC systems are as follows.

- A grid-connected energy system is an independent decentralized power system that is connected to an electricity transmission and distribution system (referred to as the electricity grid). They are ideal for locations close to grid.
- The operational capacity is determined by the supply source. The system functions only when the supply sources are available.
- Because of the supply driven operation, the system may have to ignore the local demand during times of unavailability of supply sources.
- The system could be either used to meet the local demand and surplus can be fed to the grid, or otherwise, the system may exist only to feed the grid.
- The connectivity to grid enables setting up relatively large-scale systems and hence they can operate at high plant load factors improving the economic viability of the operation.
- In a grid-connected power system the grid acts like a battery with an unlimited storage capacity. So it takes care of seasonal load variations. As a result of which the overall efficiency of a grid-connected system will be better than the efficiency of a stand-alone system, as there is virtually no limit to the storage capacity, the generated electricity can always be stored, and the additional generated electricity need not be "thrown away".
- In addition to the initial cost of the system, cost for interface of the system with grid is incurred.
- For systems operating on renewable sources like biomass, wind and solar PV, there will be a high pressure on these renewable sources, as the system usually operates at high scales and need more biomass for its operation [3,5].

2.2. Stand-alone systems

Stand-alone systems produce power independently of the utility grid; hence, they are said to stand-alone. These are more suitable for remotest locations where the grid cannot penetrate and there is no other source of energy. Stand-alone systems comprise the majority of photovoltaic installations in remote regions of the world because they are often the most cost-effective choice for applications far from the utility grid. Examples are lighthouses and other remote stations, auxiliary power units for emergency services or military applications, and manufacturing facilities using delicate electronics. The SA systems suffer from innate disadvantages like low capacity factor, excess battery costs and finite capacity to store electricity forcing to throw away the extra energy generated [10]. The important features of SA systems are as follows.

- In SA energy systems, the operational capacity is matched to the demand.
- The needs of the local region assume maximum priority.
- These systems are ideal for remote locations where the system is required to operate at low plant load factors.
- Operation is mostly seasonal, as the typical stand-alone systems are usually based on renewable energy technologies like solar PV, which is not available throughout the year.
- This does not exert pressure on biomass and other renewable energy sources as it requires fewer resources for small-scale applications.
- These systems are not connected to the utility grid as a result of which they need batteries for storage of electricity produced during off-peak demand periods, leading to extra battery and storage costs, or else the excess power generated has to be thrown away.

2.3. Grid-connected systems vis-à-vis stand-alone systems

Even though both GC and SA are beneficial in their own right, the choice of GC or SA system depends on number of factors. First of all, both of them mostly operate on renewable energy sources so there is a significant reduction in the emissions and climate change can be satisfactorily mitigated. Nevertheless, stand-alone systems are preferred when accessibility is the central issue and are suitable to supply electricity to hilly regions and remote villages.

Apart from accessibility and climate change benefits, the decision to adopt GC systems or SA systems is also driven by economic feasibility and load factors. In GC systems any surplus power can be fed back to the grid. Therefore low load factors which are typifying characteristics of rural electricity scenario do not affect GC systems, since grid acts as an infinite storage unit facilitating continuous operation of the system also eliminating additional costs on storage batteries in case of wind and solar PV. But the extension of the grid to some remote places becomes prohibitively expensive. In such locations SA systems are inevitable choices. Therefore it is important to study the necessary and sufficient conditions under which the SA and GC become feasible. In the following sections articles pertinent to feasibility analysis of GC and SA are reviewed to facilitate an objective assessment for making appropriate choice of technology under different scenarios. The important technologies that are available for decentralized power generation in GC and SA mode and their features are summarized in Table 1.

3. Review of studies in GC and SA—current status

To the best of the knowledge of the authors, there is perhaps, so far no review presented on the studies focusing on assessing the feasibility of grid-connected and stand-alone energy systems. Hiremath et al. [4] and Jebaraj and Iniyan [15] have published reviews on decentralized energy planning models and energy models respectively but have not focused on GC systems and SA systems. In addition to these reviews, isolated case studies and applications pertaining to GC and SA systems are presented in detail. For example, Stone et al. [16] presented case studies of implementation of stand-alone solar PV projects, biogas installations for the electrification of villages in Sunderbans, India. The report presents the investment and operational costs along with the impact of rural electrification project initiative of successfully implementing three hundred solar PV powered home lighting systems at a place that suffered a pathological electricity accessibility crisis. Currently around 4500 customers are provided home lighting. Ravindranath and Hall [17] have presented a case study in which they have discussed system configuration, operational details, and costing of a biogas unit in Ungra village, Karnataka, India. A comprehensive set of case studies is presented by Hiremath et al. [18] discussing the total potential, installed capacities of decentralized energy systems in both SA and GC mode in selected states of India. In all these studies what is missing is but a generalized methodology for assessing the feasibility of GC and SA decentralized energy systems. As argued by Reddy et al. [19] the choice of technology is very important for quality energy services and in that direction the current paper attempts to review studies in GC and SA systems carried out so far in trying to capture the knowledge available to feed into the process of assessment of feasibility of GC and SA decentralized systems.

The literature studies are presented here in the order of activities followed to successfully install an energy system. Techno-economic analysis and environmental feasibility studies are presented as a first step. Later, the issues of how to design a system that can function efficiently under given conditions are presented. This section also looks at various performance evaluation indicators, design alternatives and optimum design that depend on number of factors such as geographical location, availability of local resources and demographic structure of the region of interest. The policy initiatives adopted for disseminating GC and SA is consolidated from different studies. Mathematical models and simulation models that are implemented to study the sensitivity of the system behavior to the system design parameters are discussed separately. Conclusions are drawn by analysis of the findings of the research articles.

4. Techno-economic and environmental feasibility analysis of GC and SA systems

Irrespective of whether the system operates in GC mode or SA mode, the assessment of the energy system for its techno-economic and environmental feasibility is imperative if the system has to function satisfactorily. The assessment begins with evaluating the technological appropriateness, economic viability and other financial incentives of a technology for it to get successfully disseminated at a given location. There are a large number of papers discussing the economic viability of the GC systems.

Table 1
Comparative description of different decentralized technologies.

Technology	Features	Suitable mode (GC/SA)
Co-generation	The average efficiency of co-generation systems is estimated to be 85%. The important co-generation technologies are bagasse co-generation, steam turbine combined heat, gas turbine combined heat	Both GC and SA
Small and mini-hydro power	The small and mini-hydro power generation systems are environmentally benign as it is run of the river technology where the river flow is not impeded; as a result the river flooding problem is eliminated. The system is classified as small-hydro if the system size varies between 2.5 and 25 MW, mini-hydro typically falls below 2 MW, micro-hydro schemes fall below 500 kW and pico-hydro below 10 kW capacity	SA
Solar PV power	Efficiency of commercially available solar PV varies between 7 and 17%. Because of its high initial investment, cost of generation per kWh becomes high making it unaffordable	SA
Wind power	Similar to PV systems wind energy systems are also site and season specific. Wind energy systems mostly operate in grid-connected mode, but only in a few villages isolated systems are operated to provide electricity for water pumping	GC
Biomass power		
Producer gas	Producer gas is the consequence of modern use of biomass and its conversion to higher forms of gaseous fuel through the process of gasification. For small-scale applications, biomass requirement range from about 5 kg/h up to about 500 kg/h	Both GC and SA
Biogas	The gas that is produced through anaerobic digestion of biomass and other wastes like vegetable residues, animal dung, etc. is called biogas. Biogas generally is 60% methane and 40% carbon dioxide	SA

Sources: Refs. [9–14].

Siyambalapitiya et al. [20] discussed importance of the pre-evaluation of techno-economic-social parameters of the GC systems. The authors feel that, one of the main reasons for not extending the grid to rural locations is because; the electricity consumption is mainly driven by domestic applications. As a result, the energy systems are forced to operate at low loads making the system to experience unwarranted load aberrations that strongly cripples the system reliability.

Reddy et al. [19] highlighted the importance of the choice of technology for improved energy services, which is of paramount importance in the development of the rural regions. A detailed evaluation of centralized technologies, decentralized technologies and energy conservation technologies were presented in addition to comparison of their costs for useful energy, using life cycle costing method. Bernal-Agustin and Dufo-Lopez [21] performed economic analysis on the GC solar PV system connected to the Spanish grid. Using net present value (NPV) and payback period (PP) parameters, the profitability of the system was studied. The system was evaluated for its economic as well as environmental benefits and the results clearly showed that the system is profitable enough to be invested in, but very long pay back periods were dissuading the investors. The Intermediate Technology Development Group (ITDG) report [22] enumerated factors that can drastically reduce the cost of grid connection and the important ones are the voltage and proximity of the grid, and availability of a step down transformer in the region of study. An extensive financial analysis of grid-connected wind energy systems of the entire Greek state was performed by Kaldellis [23]. Bakos and Tsagas [24] have performed techno-economic assessment to determine the technical feasibility and economic viability of a hybrid solar/wind installation to provide residences in Greece with thermal and electrical energy. The energy output of the hybrid system was estimated using a simulation model and using Life Cycle Costing (LCC) method, the payback period was determined. The Ministry of New and Renewable Energy (MNRE) annual report, 2004 [25] discusses how attractive GC systems are in the context of Clean Development Mechanism (CDM). Life Cycle Analysis (LCA) was performed to assess environmental benefits of solar PV systems, the effects of application Kyoto protocol, and reduction in emissions.

Similar studies have been conducted for SA systems. Khan and Iqbal [10] feel, that the potential solution to the problems of SA systems like low capacity factors, excess battery costs and limited capacity to store extra energy is to use the SA systems as a hybrid with other sources of energy carriers. Both renewable and non-renewable carriers are discussed with their potential in terms of cost effectiveness and environmental friendliness. HOMER software was used to optimize and arrive at the right combination of energy systems. The results based on the existing costs revealed that the wind-diesel-battery hybrid system was economical and due to severe cost constraints, an environmental friendly hydrogen based hybrid system is not effective. Kolhe et al. [26] assessed economic viability of a stand-alone solar PV system along with a diesel-powered system. The sensitivity analysis revealed that, even under unfavorable economic conditions, the solar PV performed better for an energy output of 15 kWh per day. When the economic conditions are more congenial, the solar PV was competitive up to 68 kWh per day. Chakrabarti and Chakrabarti [27] have built a strong case for solar energy based SPV stand-alone system by conducting a feasibility study in an island called "Sagar Dweep" in West Bengal in India based on socio-economic and environmental aspects. The authors compare the generation costs of SPV and conventional power systems to illustrate how conventional power systems suffer from diseconomy when power needs to be transmitted to extremely remote locations. The social viability of SPV was apparent from a conspicuous improvement in education, trade, commerce and increased participation of women in activities other than household chores in the island. The environmental advantages are accounted for by indirectly calculating the externality costs of different fossil fuels and by noticing the absence of these costs in case of SPV.

Kumar et al. [28] calculated the power costs and optimum size of a stand-alone biomass energy plant based on three types of fuels namely agricultural residues, whole forest, and residues of lumber activities. Rana et al. [29] made an attempt to arrive at a least cost matching of stand-alone electricity generation technologies and the type of energy resource available in the villages of Madhya Pradesh in India. This matching facilitated classification of villages into five categories on the basis of energy resource potential and suitability of technologies.

Ravindranath et al. [30] have compared bioenergy technologies (BETs) with fossil fuel alternatives and traditional biomass energy systems to assess the carbon abatement potential of BETs. They have estimated the incremental cost of carbon abatement by evaluating the replacements of seven conventional alternatives by ten BETs projects and it was found that six projects indicated negative incremental cost for carbon abatement suggesting the fact that BET implementation is promising in carbon abatement in lieu of conventional alternatives or traditional bioenergy systems.

A note worthy observation here is that there are not many studies to assess the environmental feasibility of SA systems which reinforces the notion that utility of SA systems is more of accessibility driven than due to environmental considerations. Financial feasibility analysis is performed from the market and entrepreneurial interests to explore the financial incentives, and other subsidies that make the business attractive. But there is no way one can afford to ignore assessment of the systems for their techno-economic-environmental feasibility as these parameters are location specific and the successful operation of the systems entirely depend on these parameters at a given region. It is also observable that systems which are uneconomical for a given load factor may become feasible for higher load factors. This opens up the discussion on what should be the ideal size, capacity factor and load factor range for which the system becomes feasible. Some of these questions were answered in the literature using optimization models. But it acts as a background for the design of the systems, which will be discussed in the next section.

5. Designing GC and SA systems

The primary objective of design of the system is to improve the quality of power for a given load factor and to achieve this in an optimal way. This depends on parameters like the population, demand, and proximity to grid. There is a huge knowledge base available in studies of design of both GC systems and SA systems. Different techniques like optimization, simulation and other mathematical modeling tools have been used for this purpose.

5.1. Engineering design of GC and SA systems

The engineering design refers to design of capacity, right sizing of the system, optimal design for increased reliability and improvements in efficiency.

Sidrach-de-Cardona and Lopez [31] quantified energy losses and the most relevant performance parameters of a 2 kW, grid-connected photovoltaic system in Spain. A generalized model to evaluate the performance at different regions, climate conditions and irradiation was developed. Salas and Olías [32] presented an extensive analysis of all the electrical parameters of grid-connected solar inverters for applications below 10 kW. The paper is a compilation of manuals and design data handbooks of over 50

manufacturers and 500 different models, and their electrical input and output characteristics.

Atikol and Guven [33] aimed at right sizing of the grid-connected cogeneration systems based on electrical load and thermal load in textile industries in Turkey, to maximize the efficiency which would simultaneously ensure maximum export of electricity to the grid. Surprisingly, it was found that, by 2020, Turkey would save $72.6 billion, and also reduce primary energy requirement by 11% if cogeneration systems were deployed. Schmitt et al. [34] have designed a range of (10, 15, and 30 kW) solar–diesel hybrid system micro-grids which could provide, if implemented, energy to 90% of the villages in developing countries. Nayar [35] described design configuration of switched/series/parallel hybrid systems along with results of few installations of solar/wind/diesel hybrid systems which are capable of providing continuous grid quality energy supply to remote locations of Australia.

Kaushika et al. [36] felt that the quantum of electricity generated could be increased by the right sizing and alignment of the arrays in a solar PV system by replacing the traditional single aperture system by interconnected arrays. A simulated model is presented to arrive at the right size of stand-alone solar PV systems, the risk associated with failure of power supply was connoted by a factor called loss of power supply probability (LPSP), which is the probability that the PV modules together with battery will fail to supply power on an arbitrary day. In addition to simulation, a linear programming model was adopted to optimize the number of PV modules and batteries.

Lietzmann et al. [37] explained the importance of dimensioning of a solar–wind hybrid energy system and formalised the procedure of exact determination of the energy potential and demand on site for dimensioning the system configuration. Elhadidy and Shaahid [38] have recorded and analyzed the wind speed data in Saudi Arabia to determine the potential when used in hybrid with diesel system, to meet the load requirements of hundred residential buildings with two bedrooms each. The evaluation of this hybrid system revealed that with increase in number of days of battery storage, the pressure on the diesel back-up system reduced. Santarelli et al. [39] assessed the design methodology of a stand-alone system, by integrating renewable energy systems such as solar PV, wind energy, and micro-hydro turbine with stand-alone hydrogen based energy systems for a mountain environment in Italy, based on energy analysis, electricity management and hydrogen management.

Dosiek and Pillay [40] have studied the design of a horizontal axis wind SA systems by simulation using MATLAB/SIMULINK. Simulation of wind turbine over a long period of time using with one Hertz resolution was also presented. The results were validated with actual data to test the proposed wind generator design. Ramakumar et al. [41] describes a knowledge based approach for the design of integrated renewable energy systems (IRES) which is a combination of two or more renewable energy based power systems, usually operating in stand-alone mode. The system reliability is quantified using LPSP.

Ilkan et al. [42] explored the option of using renewables to reduce the level of peak demand in N. Cyprus, which being a Mediterranean island had immense potential in solar and wind energy resources.

5.2. Institutional design of GC and SA systems

Institutional design includes critical investigation of the rural electrification problem specific to a geographical location, finding the optimal solution and designing a location-specific strategy within the ambit of the institution for successful implementation of the solution. If the solution fails to deliver the expected output, the raison d'être for the failure has to be critically assessed and diligently followed by system redesign.

Walker [43] assessed the linkage between stand-alone systems and fuel poverty in UK. The paper highlights both positive links and risks that are associated with adopting stand-alone systems for meeting the energy needs of low-income households. The author objectively establishes the fact that it is only by adopting decentralized power supply strategy in the future, that carbon-zero homes can become a reality in UK.

Hoogwijk et al. [44] reveals some of the facts about geographical, technical and economic potential of wind across the globe. The Australian Business Council of Sustainable Energy (BCSE) [45] provided a set of guidelines like wind energy assessment, improving quality of power, generator run time, site selection, towering, protection from lightning and other design issues for design of SA wind systems.

Mayer and Heidenreich [46] present a few case studies to prove that the poor performance of the PV SA systems need not only mean that the system is facing technical problems, but it might also be due to factors like mismatch between the generation potential and load factor, poor sizing and other systemic problems. In the current paper authors have examined the critical factors for failure of a stand-alone PV system. The authors have highlighted the limitation of current coefficients and developed new coefficients which make better performance indices over the existing ones for SA systems.

Rabah [47] describes the case study of practical implementation of a stand-alone solar PV to improve the quality of life of poor in Kenya where 80% urban and 99.5% rural households do not have access to grid. Ramakumar et al. [48] used knowledge based design tool called IRES-KB for analyzing design scenarios of different energy systems like biogas system, wind energy system, SA systems, and other integrated renewable energy system (IRES).

Holland et al. [49] has made a series of propositions about the critical factors like institutional support, local ownership and local participation, market aspects and other energy management issues based on case studies learning, for successful diffusion of stand-alone systems in rural regions. Bates and Wilshaw [50] present a report summary of the status of solar PV power systems, governmental policies towards renewables, and key market barriers for the successful and quick diffusion of solar PV power systems. Mukunda et al. [51] reported experience at ASTRA, IISc with stand-alone bio-residue based power systems, comparison of alternate energy systems based on initial investments, gestation period and energy. Dasappa et al. [52] have presented case studies of isolated biomass gasifiers being used to provide low temperature and high temperature thermal requirements of industries. The paper also gives the configuration and operational details of these systems. Similarly Global opportunity fund (GOF) in its first quarter report [53] presents cases from bagasse co-generation for grid in Indian sugar mills from the states of Maharashtra and Gujarat. It consists of a detailed report of the capacities and other operational details. Gulli [54] has evaluated the social-cost benefit of stand-alone combined heat and power (CHP) systems with centralized power systems considering both internal and external costs of the system. Miller and Hope [55] have summarized the lesson learnt from lending loans to India, Sri Lanka and Indonesia for off-grid solar diffusion in rural electrification.

6. Policy measures and barriers for successful implementation of GC and SA systems

The implementation of energy systems will be successful only if policies are clearly stated and presented to the stakeholders. The stakeholders may include the local government willing to improve the energy situation, private investors and most importantly

consumers. Stakeholders might also include international agencies and NGO's. There is vast amount of policy related information reported in literature that is critical to successful dissemination of energy technologies.

Martinot [56] has extensively discussed the policies, strategies and lessons learnt from the GEF (Global environmental Facility) project on the status of grid-based renewable energy systems in developing countries. Gupta [57] discussed advantages and policy approach in India for grid based RETs. Survey of renewable energy in India [58], is a report prepared by TERI which indicates that status of grid-connected power supply market is at a technology demonstration and validation stage in contrary to the developed countries. Faulin et al. [59] have justified the potential of RETs in generating local employment which has resulted in equal distribution of employment with the help of case studies from Navarre, Spain where 60% of energy consumption is sourced through the renewables. Freeman [60] introduces a pre-paradigmatic notion of a controlled demand for GC systems managed by independent service operators (ISO) either by reducing demands by demand response programs or increase the generation if it is within reason for the grid or import power to meet the needs of the customers.

Adnan [61] asserted the need for increasing cooperation between the 10 member nations of Association of Southeast Asian Nations commonly referred to as ASEAN to duplicate the grid-connected biomass power generation systems throughout the ASEAN. He also discussed benefits of biomass residue resources, and also optimization of their availability to achieve self-reliance in power generation and avoid over dependence on fossil fuels.

A generalized framework to assess the factors affecting the successful completion of grid-connected biomass energy projects was developed and validated with real world data of power plants in Thailand by Carlos and Khang [62]. It was found that at different phases of the project each stakeholder has a different role to play. It was accepted that political and regulatory framework played a very crucial role in overall completion of the project.

The number of studies on policy aspects of SA systems is quite large because these systems can be successful only if there is local, institutional and government support. Hence we can find emphasis on policy formulation as a means for effective dissemination and operation of the systems. The goal in policy formulation is to design a framework for delegating authority and responsibility of maintenance of the system at a given location. This also includes formation of hierarchy in the decision making body by encouraging local participation. The policy frameworks also include creation of mechanisms for educating the rural people about the importance of self-reliance in energy, role of energy systems in creation of local employment and resulting increase in income, which can improve the standard of living.

7. Mathematical modeling of performance of GC and SA systems

The most efficient approach to optimize the system performance is through mathematical modeling. The mathematical models map the abstract real world into a world of comprehendible and interpretable numbers. In doing so, if only those parameters which have a negligible effect in the abstract real world are ignored in the mathematical model, then the real world is fairly captured by the model. These decision support systems based on the models can be used not only to optimize the system operation but also to design the favorable design and operational characteristics of the energy systems.

Fernandez-Infantes et al. [63] developed a computer-based decision support system to design the GC PV system based on electrical, environmental and economic considerations. To reduce energy demand, basic energy saving rules like discarding old and obsolete energy guzzling devices, awareness campaigns among students to teach them not to waste electricity, stop using electricity for heating applications, were proposed. Ro and Rahman [64] developed a controller system to improve the system stability of fuel cell GC systems in power distribution network, and its effectiveness was tested using a computer model. Nakata et al. [65] use non-linear programming optimization model and METANet economic modeling system developed at the Lawrence Livermore National laboratory for arriving at system configuration, and operation of hybrid systems for the supply of heat and power in Japan. El Bassam and Maegaard [66] strongly feel that there is a need for following systems approach to model any decentralized energy system meeting the energy needs of rural communities. Kasseris et al. [67] developed the optimization of the wind-fuel cell hybrid system for larger output under strict and lenient grid network restrictions. Ackermann et al. [68] developed an economic optimization tool to evaluate different options for distributed generation, and improve power quality of an embedded wind generation system in weak grid conditions and validated the model with the help of simulation.

Similar studies were carried out for SA systems modeling. Pelet et al. [69] adopts multi-objective evolutionary programming technique to rationalize the design of energy systems for remote locations. A comparative study was conducted by Kamel and Dahl [70] using optimization software called HOMER (hybrid optimization model for electric renewables), to assess the economics of hybrid solar–wind systems against the diesel.

Lindenberger et al. [71] analyses modernization options for a local energy system, from the perspective of both demand reduction and supply-related measures. An extension of the optimization model deco (dynamic energy, emission, and cost optimization) was adopted. Santarelli and Pellegrino [72] developed mathematical optimization model to minimize the total investment cost of a hydrogen based stand-alone system to supply electricity to residential users, integrated with renewable energy systems like solar PV and micro-hydro. The structure of the energy plant forced the problem to be of the nature of a black box problem, in which the logic of the simulation program captures the constraints of the problem, and the objective function and constraints do not have a great bearing upon decision variables. The problem was solved using modified downhill simplex algorithm, which was used in most of the applications to solve black box problems.

Mahmoud and Ibrik [73] used computer-based dynamic economic evaluation model with five economic efficiency indicators to assess three supply options namely solar PV, diesel generators in stand-alone mode and grid extension. Gabler and Luther [74] developed and validated a simulation model and optimization model for a wind–solar hybrid SA system to optimize the design of converters and storage devices of the SA systems so as to minimize the energy pay back time which is the ratio of investment on energy to the power delivered. Meurer et al. [75] enunciated generation of measurement data of performance of an autonomous SA hybrid renewable energy systems (RES) to optimize the energy output and operational reliability with the aid of simulation programs. Manolakos et al. [76] developed a simulation based software tool for optimizing the design of a hybrid energy system consisting of wind and PV to supply electricity and water for a remote island village. Replacement option of conventional technologies with hydrogen technologies, fuel cells in an existing PV-diesel operated in stand-alone mode was simulated and optimized by Zoulias and Lymberopoulos [77], using the hybrid optimization model for electric renewables (HOMER) tool for techno-economic evaluation and optimization.

Schmid and Hoffmann [78] expressed their concern over two major challenges in the Brazilian Amazon region of alleviating the discomfort for local habitants and reduce the subsidies for diesel in the local grid utilities. The simulation results showed that PV systems with energy storage in conjunction with existing diesel generators, allowing them to be turned off during the day, provide the least energy cost solutions at locations where transportation costs do not affect the diesel prices. But at locations where diesel prices shot up due to increased transportation costs, the system becomes economical at above 100 kW scales. Kelouwani et al. [79] studied steady state and transient behavior based on voltage, current and temperature for a wind-PV SA RES with hydrogen. This was done for validating experimental data with simulation model in order to provide a footprint for developing effective algorithms to optimize RES in stand-alone mode. Abouzahr and Ramakumar [80] presented a closed form solution method to evaluate LPSP for SA wind electric conversion system with energy storage. The method was also used for a single-axis solar PV stand-alone system [81] to optimize the total system cost with the help of a numerical example. Vosen and Keller [82] developed optimization and simulation model for a SA solar powered battery-hydrogen hybrid system for a fluctuating demand and supply scenarios using two storage algorithms for with or without prior knowledge about the future demand. Jeong et al. [83] proposed a fuzzy logic algorithm as a strategy for effective load management which results in improved endurance and system operation efficiency of a hybrid fuel-cell and battery stand-alone system.

Joshi et al. [84] developed a linear mathematical model to optimize the energy mix of different energy source-end-use conversion devices to supply energy to a typical Indian village by The model was run for both domestic and irrigation sector. The results showed that for lighting electricity was the best option and for irrigation pump sets, diesel based pumps fared better than electricity pumps. For cooking, both biogas and agro waste were found to be feasible.

The modeling and policy formulation activities are not independent of each other, but compliment to each other by one following the other. That is, based on the results of the mathematical model; suitable policies have to be formulated in the direction of implementation of the results. So, there is a certain amount of overlap among these activities. Efforts in modeling of SA systems appear to be quite abundant in the literature and this is perhaps due to the luxury in terms of time, data availability and completeness in studying all the aspects of an isolated system.

8. Role of GC and SA energy systems in climate change mitigation

Climate change mitigation analysis refers to all the activities aimed at quantifying, projecting and evaluating the opportunities for reducing the greenhouse gases in the atmosphere in both developing and developed nations.

Ravindranath and Sathaye [85] have, in their book "Climate Change and Developing Countries" expatiated upon the opportunities in the energy sector for greenhouse gas mitigation. They feel that by making appropriate shifts towards energy efficient technologies and fuel substitution, greenhouse gas emissions can be reduced to a large extent. With climate change mitigation as the objective and keeping in mind the importance of the choice of energy technology and fuel shift in this endeavor, the literature exploring the role of GC and SA in climate change mitigation is presented in the ensuing section.

Using India as a case study, the potential role of biomass in global climate change mitigation was discussed by Kishore et al. [86]. The core issue discussed in the paper was the extent of commercialization and mainstreaming of biomass energy technologies within the framework of clean development mechanism (CDM). The paper emphasizes the need for promoting biomass energy technologies to develop village infrastructure and village power. Despite the luxury of packaging of GC systems under CDM projects, they do not provide power at village levels or to village clusters. Whereas the SA system apart from its strict adherence to the motto of CDM can be exclusively devouted for meeting village energy needs.

With the help of case studies in two small villages, Ungra and Hosahalli in India, Ravindranath [87] shows that by using only 16% of wasteland in India for biomass power (16 Mha of the total 100 Mha), 5.5 lakhs villages could become energy self-sufficient. Since village loads typically vary between 2 and 20 kW it is always possible to have village level stand-alone biomass energy systems to satisfy the domestic and shaft power needs of all the villages. The paper also shows how growing biomass on degraded land for power at a sustainable rate can help in carbon sequestration. A study was conducted in India to assess the carbon abatement potential of stand-alone solar home systems (SHS). SHS are being promoted and disseminated by government to meet lighting needs of villages. These SHS can contribute directly to reduction in carbon emissions in India in two ways - first by replacing kerosene-based lighting in around 67 million households and secondly by avoiding the carbon-intensive grid extension to less inhabited villages [88].

A detailed estimation of small hydro power (SHP) potential in India under CDM was presented by Purohit [89]. The author has demonstrated that the SHP projects (both SA and GC) are attractive under the CDM. It was estimated that technically feasible SHP has an annual certified emission reduction (CER) potential of 24 million in India. Bagasse cogeneration projects were also found to be financeable under CDM with a total CER potential reaching as much as 26 million [90]. Similar study was conducted to determine the economic potential of CDM projects in grid-connected electricity generation using surplus bagasse from sugar mills in Indonesia. It was found that the bagasse cogeneration had a potential of 260,253 MWh of electricity generation per year resulting in a reduction of 198,177 tonnes of CO_2 and earning 1.12 million US dollars per annum [91].

In addition to packaging decentralized energy projects under CDM, several authors have studied the operational difficulties in getting CDM sanctions for these projects.

Adhikari et al. [92] presented an overview of CDM portfolio in Thailand by cataloguing potential, opportunities and barriers for executing decentralized sustainable renewable energy projects in the context of CDM. The economic, environmental and sustainable benefits as well as removal of barriers for satisfactory dissemination of important RES technologies namely stand-alone small hydro, stand-alone SPV, grid-connected wind, geothermal and Ocean energy were studied in detail under the CDM umbrella [93].

Tsikalakis and Hatziargyriou [94] have proposed a method to calculate the GHG emissions from stand-alone power generation and quantification of the benefits. The paper warns of misleading results by using average values for emissions. The participation of distributed energy systems in trading market was also studied and they were found to displace significant GHG emissions provided sufficient incentive was available from market participation.

It was also found in the literature that number of authors have attempted to study the market potential of RES under the CDM cover. The studies unequivocally suggest that CDM support can play a major role in reducing the cost burden on the renewable energy projects in developing countries enabling them to successfully implement these projects in rural regions which can help these countries to improve the rural infrastructure and promote sustainable development. Lybaek [95] has assessed market opportunities in Asian countries for SA biomass CHP. The author has presented the methodology to be adopted to

finance these technologies under CDM. He has substantiated it through a case study in small and medium enterprises (SME's) in Thailand and establishes the fact that the decentralized biomass CHP projects are technically and financially viable under CDM. Silveira [96] also explored the potential of CDM in promoting bioenergy technologies to promote sustainable development in developing countries. It is illustrated how CDM can apart from GHG emission, be used to disseminate renewable energy, reduce investment risks and create employment.

9. Studies based on the comparison of both GC and SA systems

Most of the studies focus only on GC systems or SA systems. Studies pertaining to the comparison of GC systems with SA systems for their techno-economic-environmental feasibility are scantily available. In one such unique study, technical and financial viability analysis of renewable energy systems with/without grid connectivity for a hotel with 100 beds was presented by Dalton et al. [97]. Net Present Cost (NPC) was used as the criteria for assessment. Results of the HOMER software indicated that grid-connected hybrid SPV-Wind RES was comparable to grid electricity, even though it is self-sufficient to meet 100% demand; it was uneconomical given the current prices. The result also showed that 65% reduction in carbon is possible with GC hybrid RES with a payback period of 14 years.

Banerjee [14] has reviewed different technological options for distributed generation, their current status, future potential, and cost of generation in India based on annualized life cycle costing method. Oparaku [98] studied financial feasibility of grid-connected PV systems with additional cost of grid extension to 1.8 km, costs of centralized (grid connected) PV was compared with centralized diesel generators and cost comparison was made between stand-alone domestic PV with stand-alone gasoline generators. In a fact sheet on GC solar PV systems, the report discusses general information about the technology and issues that have to be considered for siting solar PV systems. The report also discusses the most suitable mode of operation (GC or SA mode) for different applications. Off-grid solar electric homes offer comfortable lifestyles with 1- to 3-kW solar electric systems. Compared to current utility power prices, the grid-connected solar electric system ceases to be cost effective. The report suggests planning strategies such as evaluating electricity needs, incorporating energy saving measures as to derive maximum benefit of SA/GC solar electric systems [99]. Brenner [100] calls for research in the domain of SPV to improve its performance. The author has argued that the electricity grid, when it exists, indubitably is the best possible way of meeting electricity needs. By comparing the costs of electricity for solar homes and ordinary homes with/without access to grid, the author has reached a conclusion that whenever grid connectivity becomes expensive and expedient, SPV is the best alternate solution and hence calling for active research in this domain.

Ramanathan and Ganesh [101] followed goal programming approach to evaluate five different electricity generation options with nine objectives representing the economic, energy, and environmental systems. The results of the model and sensitivity analysis however encouraged stand-alone PV and Diesel systems for households, but the grid electricity and gasification were recommended only after improvement in the efficiency of operation and generation. Experience of simulator for a renewable energy system with wind, solar, energy storage and stand-by plants in both grid-connected and stand-alone modes is modeled and scheduling of stand-by plant and grid interaction was optimized by Mitchell et al. [102]. The model showed Law of diminishing returns effect, in which complete energy independence would be achievable, but becomes prohibitively expensive.

Economics of grid electricity was compared to the stand-alone biomass gasifier, solar pond and a decentralized wind energy systems by Sinha and Kandpal [103] from the perspective of total cost of generation per kWh, the transmission and distribution losses and load factors. A broad-based, generalized cost function was derived for an isolated village and a cluster of villages under rural electrification scheme. The study reiterates the need for decentralized energy options for successful rural electrification.

Bouffard and Kirschen [104] have envisioned the need for a highly autonomous stand-alone renewable energy supply systems to control the imbalance in electricity supply chain comprising of centralized power systems. The imbalance, they argue, is due to a number factors namely depletion of fossil fuels, climate change concerns, geopolitical disruptions and economic risks which discourage investors into centralized supply chains and encourage them to look more towards alternate, robust renewable energy based supply systems.

Beck and Martinot [105] highlighted the policies and key barriers for diffusion of SA systems and GC systems like unfavorable pricing rules, private ownership, and lack of locational pricing leading to undervaluation of GC systems. Pelet et al. [69] have shown that it is difficult to economically diffuse solar systems with short-term benefits in the mind.

10. Conclusion

A good number of articles have presented both success and failure stories of implementation of SA as well as GC systems. But most of the articles are context dependent and were applied to isolated cases. A generalized approach to assess suitability of SA and GC systems at a given location, based on techno-economic-financial-environmental feasibility does not find adequate coverage. If data pertaining to system costs, operation, maintenance and other relevant cost details are made available along with the learnings from the case studies, the economic-financial assessment objective could be easily accomplished. It was found that the techno-economic assessment of grid-connected systems and stand-alone systems is restricted to annualized life cycle costing (ALCC) methods. Computer-based technological assessment tools in combination with material flow analysis (MFA), substance flow analysis (SFA), life cycle assessment (LCA) finds little reference in the literature. For a realistic estimate it is important to capture uncertainty in systems and hence stochastic modeling and simulation studies have to be encouraged in the field of energy studies. It is also clear from the literature that SA systems do not enjoy the CDM support. It is therefore important to realize the potential of SA systems in GHG emission reduction in developed countries and their role in promoting sustainable rural development in developing countries. Successful implementation of SA projects under CDM requires devising suitable policy measures after taking cognizance of local support, institutional barriers and other social factors. This necessitates combined efforts from policy makers and modeling experts to study the systems collectively with other allied interdisciplinary sciences, for a clear representation of the energy problem and effective implementation of the solutions.

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